A Conceptual Framework for Construction Safety Training using Dynamic Virtual Reality Games and Digital Twins

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Abstract –
The construction industry is suffering from a high rate of accidents that significantly affect the overall performance of projects. Compared to the conventional safety training methods, Virtual Reality (VR) games offer a more immersive and interactive learning experience for the participants. However, training scenarios in most of the existing VR games lack complex tasks and the realistic environment required for actual construction. This work proposes a conceptual framework for dynamically updating VR training games through information streaming from the digital twins. The training scenarios in VR games are automatically created from the project intent information, project status knowledge, safety regulations, and historical knowledge provided by the digital twins. Therefore, construction workers can be trained in realistic training environments with relevant tasks they soon afterwards pursue. Dynamic VR training is expected mutually beneficial for enhanced digital twins and periodic construction safety management. Inadequate technology readiness level of the construction industry and difficulty in collecting good quality data are some of the major challenges for implementing this framework.

Keywords –
Digital Twins; Virtual Reality; Construction Safety; Safety Training; Human-Computer Interaction.

1 Introduction

The construction industry remains one of the most dangerous workplaces for the past several years, and the latest report shows the highest increase in fatalities since 2007 [1]. Several training sessions are conducted for construction workers to create safety awareness. However, the injury rates in the industry remain high [2], and there is a compelling need to improve safety training methods. Even though the effectiveness of traditional training methods is supported by statistical evidence, the computer-aided training methods are superior to them in many aspects [3]. Better engagement of trainees, provision of text-free interfaces and representation of actual workplaces are notable advantages of computer-aided training methods such as VR games. Besides, recent studies in VR training demonstrate the possibility of automated performance assessment [4] through run-time data collection and collaborative training using multiplayer games [5].

The Digital Twin (DT) is an up-to-date digital counterpart of the physical entities in a system [6]. The physical entities in construction include objects and processes in a construction project. The vast potential of digital twins for various applications such as construction safety, progress monitoring, resource allocation and decision making is yet to be explored. Seamless data collection and transfer through DT is possible with state-of-the-art sensing technologies. The information from digital twins can significantly improve VR training in many aspects. This study proposes a conceptual framework for dynamically updating the VR environments and task scenarios for construction safety training through digital twin technology. The possibilities and limitations of the existing technologies for this purpose are evaluated.

2 Background

2.1 Virtual Reality for safety training

VR has been an integral part of training in several industries such as construction, education, healthcare, design, manufacturing and defence. It offers a vivid, immersive and interactive experience to the users in a safe environment. Even though the earliest adoption of VR in construction dates back to the 1990s, the past decades have seen a tremendous increase in its applications [7]. The primary application areas in construction include visualisation, planning, collaboration and training related to engineering design, project management, safety, construction equipment, and workers [8, 9].

The platforms for VR vary in scale and level of immersion the users' experience. It can be stationary displays in the form of desktop computers or surrounding screens like CAVE. Other than that, VR platforms include head-mounted displays (HMD) such as helmets and hand-held displays such as tablets or smartphones [10]. Among these, HMD offers the highest level of immersion for the users. In addition to headsets, treadmills, haptic devices such as data gloves and body motion suits enable human-computer interaction through VR environments.

The serious games in virtual reality were designed to expose users to numerous situations that prepare them for future scenarios [11]. The awareness inculcated in the users through highly engaging and challenging gaming experiences would be translated into timely responses in the workplace. The workers can be trained with high-impact trade-related incidents without exposing them to dangerous conditions. Besides, construction activities often demand collaboration between various workers and trade groups. Multiplayer VR environments provide users with a collaborative experience similar to that of an actual construction site [5].

The VR technology has been extensively used for safety training in construction. However, the potential of data mining to improve the performance of the participants were not fully explored. Golovina et al. [4] proposed a method to automatically collect data related to safety violations during VR training. The object colliders of the players, hazardous objects and construction equipment in serious games collect data of close call events and harmful collisions. This critical information, which is seldom available in conventional training methods, helps to provide personalised feedback to the players. The immersion level of the players can be further enhanced by Augmented Virtuality (AV) training environments. Wolf et al. [12] deployed a modified angle grinder as an AV controller to provide the players with an enhanced learning experience and transferrable safety awareness. They furthermore implemented in-game questions through pop-up boards, which tested the players' actions and their understanding.

The VR environments were earlier criticised that their level of sophistication is less than what is required for reality [13]. The creation of VR scenarios from conception to execution is as complex as any other entertainment industry project regarding the level of details and programming efforts [14]. Some of the existing studies have proposed the use of information from BIM to enhance the VR training environments [4], [15, 16]. The current study envisions to create realistic and dynamically evolving training scenarios through digital twins of construction projects.

2.2 Digital twins for construction safety

An efficient Job Hazard Analysis (JHA) is essential for alleviating accidents in construction sites. Even in this era of advanced technologies such as Building Information Modelling (BIM), JHA is performed manually, resulting in erroneous and ineffective reporting and mediocre safety management [17]. Safety engineers are assigned to analyse the hazardous elements in each task and determine the order of priority for mitigation. They categorise the risk of the incidents by analysing their level of severity and probability of occurrence [18]. Those two measures rank the potential risk on a scale from the most negligible to the most severe outcome. The process of job site safety analysis is divided into three tasks: (a) loss-of-control identification associated job or activity, (b) assessment of the level of risk for the identified incidents, and (c) action controlling the risk to reduce or eliminate it [19].

As Sacks et al. [20] point out, federated building models representing as-designed and as-planned states of a project are not digital twins. Building information models as the digital representation of buildings or infrastructure lacks frequent as-built and as-performed states essential to understand and continuously improve the construction workflow. To make matters worse, construction safety is far behind other disciplines in BIM for which somewhat structured processes and tools exist, for example, estimating construction costs and schedules [21]. Likewise, numerous data acquisition technologies exist that hardly touch the world of construction safety [2].

There is a significant opportunity for digital twins explicitly tailored for construction safety to provide new kinds of decision support to key stakeholders. Primary stakeholders are the health, safety, and environmental (HSE) coordinators but include all others who have the same responsibility in their job profile (e.g., engineers, planners, construction managers, workers). The digital twin technology has great potential to stimulate various scenarios for construction safety research. However, many research efforts often only target the use of a singular technology without integrating the technology and subsequent analysis into a broader, more comprehensive framework for identifying and preventing hazards [15]. The current study proposes to integrate VR safety training with digital twin information streams.

2.3 Integration of Virtual Reality and digital twins

Serious games in VR have been increasingly adopted for construction safety training. Training scenarios in most of the existing VR games lack complex tasks and the realistic environment required for actual construction. This study proposes to enhance the VR training scenarios through project-specific details from the digital twin. This concept may appear ambitious considering the technology readiness level of the construction industry. Besides, data acquisition and transfer in the construction industry are much more challenging than more organised industries like manufacturing and design. Consequently, there are early attempts to integrate digital twin and VR in other industries. Even though most of these studies are on a conceptual level, there is a great possibility for their implementation in the near future.

Tao et al. [6] proposed a generic framework for integrating VR and AR (Augmented Reality) with a digital twin. The possible seamless integration of physical entities and virtual entities through interaction functions and VR/AR devices is outlined in the framework. The physical entities include machines, materials and the environment; virtual entities are their virtual counterparts. The virtual entities interact with physical entities and are synchronised through interaction functions, VR/AR devices, and sensors. The interaction functions include data import, image processing, rendering, tracking and simulation. VR/AR devices can be HMD, data gloves or handle. The digital twin data would be in the form of point clouds, images or videos. The users can experience and monitor various industrial processes in the physical entities through the virtual environment. They can intuitively perceive the internal operations in machines through immersive VR/AR devices. Examples for application of VR - digital twin integration include remote surgery [22], customised product development [23], manufacturing planning [24] and machining process monitoring [25].

3 Digital twins and Virtual Reality for construction safety

Using VR environments for teaching has throughout the literature shown more remarkable results than traditional lectures [3]. By basing the VR environment on project status knowledge (as-built and as-performed), it is possible to do learning scenarios based on real-life events for the given project. Simulating the safety status will allow for lessons learned to be transferred back to the digital twin and optimise current safety plans. Figure 1 shows the conceptual diagram of Digital Twin for Construction Safety (DTCS) and how dynamic VR training can be integrated with the DT.

3.1 Prevention through design and planning

Alternative construction plans are handed to the prevention through the design and planning module (shown in green) of the DTCS and enhanced with safety, based on the safety regulation of the construction site. The system analyses the hazard spaces identified in the design and hazard spaces identified in the process (e.g., crews working simultaneously on different stories, creating hazard zones in terms of being struck by an object from above). The safe alternative plans are returned to the Digital Twin for Production Planning (DTPP) for decision-makers' (stakeholders of the project) selection, consequently updating the baseline plan from which the construction site is built.

3.2 Conformance checking

The conformance checking module (shown in yellow) should find and classify discrepancies, including severity level, between the plan and reality. This information should be stored, and when the HSE expert has visited the problem, they can provide new information on the correctness of the output (in terms of both incident classification and its severity). This information provided by the HSE should be used to improve the classification of future occurrences and to update the best practice. An example of an updated best practice could be to use a safety net in some situations to avoid the repeated removal of a guardrail.

3.3 Right-time analysis and mitigation

The right-time analysis and mitigation module (shown in red) perform complex event processing and classification based on the reality of the construction site, the raw safety monitoring data, historical knowledge, and safety regulation. Then the workers are alerted to prevent both accidents (i.e., fatalities, serious injury, and minor injury) and incidents (i.e., close calls and unsafe acts) before they occur. The module subsequently performs an accident investigation, where the root cause of the incident or accident can be determined and prevented in the future. Besides, the feedback to and from the decision-makers are stored and used in processing/classification- and-investigation-mechanisms in this module. These are updated and used in the prevention through design and planning module (i.e., the first component of the DTCS), conceptually closing the loop of the digital twin for construction safety.

3.4 Dynamic Virtual Reality training

The dynamic VR training module (represented in blue) includes updating VR games and periodic training of workers using the latest information from the DTCS. By feeding the model with the accident type and the area, the smart VR environment can produce relevant scenarios for each incident fed into the system. This will be done based on the location and type of hazard. Both colliders and data collection capabilities will be automatically created from this scenario before a game is conducted. The workforce and the digital twin mutually benefit from this. The worker receives training, and the digital twin receives knowledge that can be utilised when other prevention approaches are used. Besides, this knowledge can be utilised when the Safety Key Performance Indicators (SKPI) are assessed for a plan.

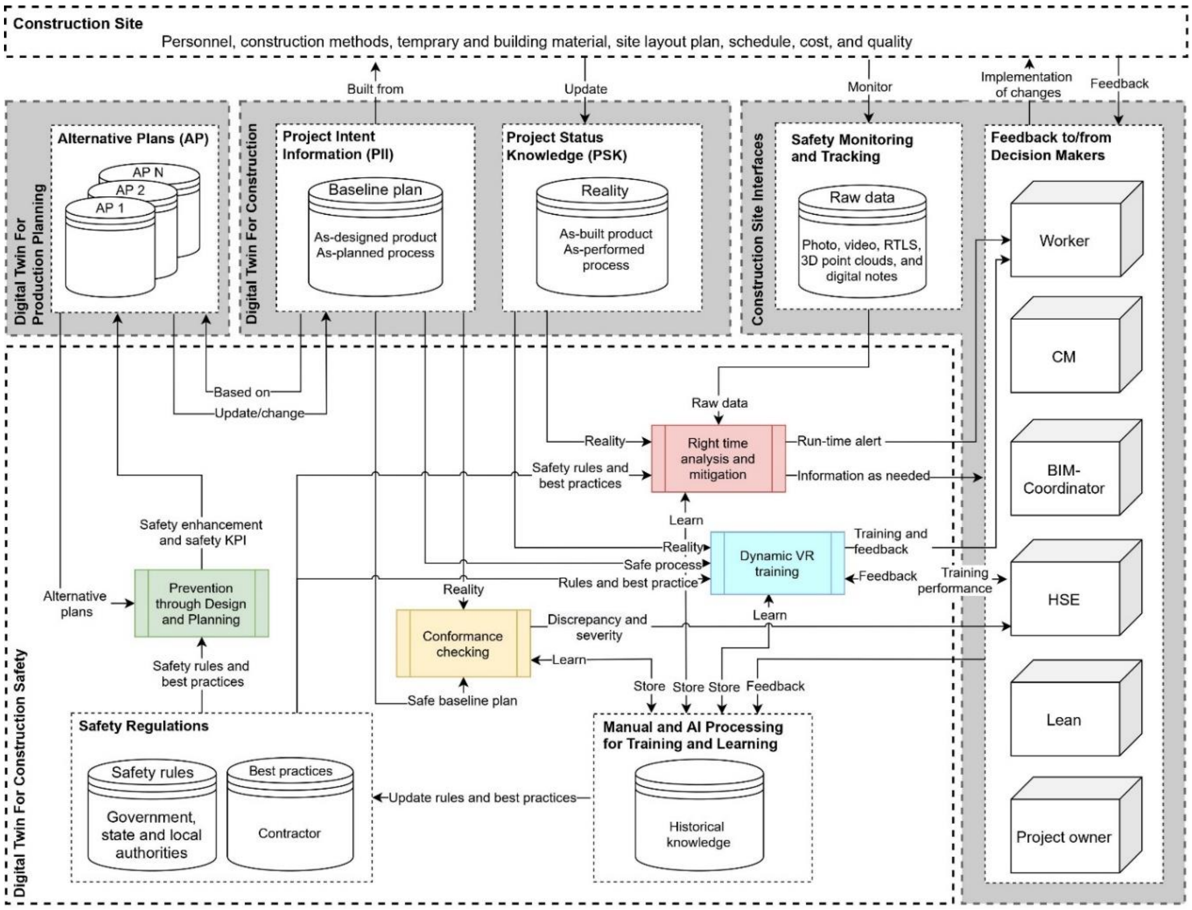

Figure 1. The concept diagram of the digital twin for construction safety and interaction between various components. The dynamically updated VR training module is presented in blue.

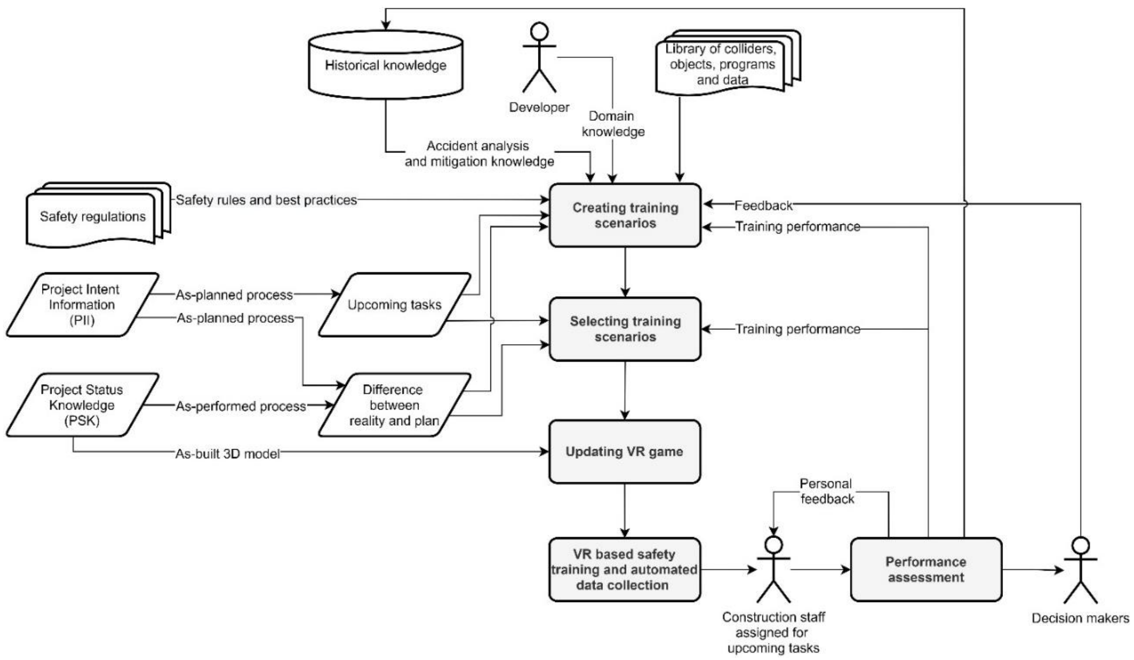

Figure 2. The framework for dynamic VR training for construction safety.

4 The conceptual framework for dynamic Virtual Reality training

A construction site is inherently complex, and the participating agents are presented with frequent unprecedented challenges. This is one of the main reasons for high accident rates, which involves even experienced workers. The accidents can be reduced to a great extend if the labours are trained in a work environment similar to what they face in real life. The dynamic VR games present the labours with training environments that are created from the digital twin of their construction site. The training scenarios are periodically updated with the progress of the work. Therefore, the labours can perform the tasks, make mistakes and learn without fearing the possibility of injury.

The conceptual framework for development and implementation of the dynamically updated VR training games are illustrated in Figure 2. The first set of training scenarios is created with information from various digital twin databases such as historical knowledge, safety regulations and a predefined object library. Then the training environments are periodically updated based on the information streams from the digital twin.

4.1 Creating and selecting initial training scenarios

Creating safety training scenarios requires geometrical information, hazardous zones and objects for interaction. The initial geometry of the training environment is created based on as-designed 3D models and training tasks based on as planned process from the Project Intent Information (PII). The geometrical information is later updated based on as-built products and training tasks based on as-performed processes from Project Status Knowledge (PSK). If there is any difference between reality and plan, the geometry and training tasks in the VR game are modified accordingly. Once the initial set of training scenarios are generated, all scenarios relevant to the upcoming tasks and work environment are selected from them for training. An example for creating and selecting training scenarios is shown in Figure 3 [26]. Here, the geometry of the building is created based on PII and PSK. The upcoming task is plastering as inferred from the project completion status. Therefore, the workers will be trained to perform plastering in the VR environment. All training scenarios relevant for plastering work are selected for updating the VR training game.

The potential hazardous zones are generated using the historical safety database and a library of predefined standard safety solutions. This library contains objects, colliders, programs and data related to probable accident mitigation methods. The objects are created to interact with the training scenarios and rectify the hazards [26]. (for example, a guard rail is used at a leading edge or a cover over a hole). This interaction is enabled by creating object colliders that can be used to ‘snatch’ objects to a location. This information needs to be created automatically for updating the VR games.

Consider Figure 3 for determining hazardous zones. This is a leading-edge scenario where a guardrail is missing. The scenario task is to locate the hazard and choose the right rectification strategy. According to safety regulations and historical knowledge, the leading-edges should be adequately secured to avoid falling from height. The current scenario task is rectifying the hazard by placing a guardrail. A specialised developer manually creates these scenarios. As new hazards can be introduced to the system using the information from the digital twin, the development is a continuous process that will be iterated throughout the project.

4.2 VR based safety training and automated data collection

Once the VR game is updated with all scenarios relevant to the upcoming tasks, the labours can be trained before their work. Each training task is designed as per safety regulations to inculcate awareness and teach best practices to the labours. The serious games are updated with potential hazard zones, construction equipment and relevant objects for interaction. Colliders are created at locations where possible interaction would result in close calls or accidents. These colliders are programmed to collect safety violation data automatically. Therefore, the VR training can provide personalised feedback to the participants. Besides, the possible accident zones can be identified before starting the work.

In the example illustrated in Figure 3, the leading-edge and the virtual avatars of the workers are assigned with safety envelopes. The safety envelops are colliders of certain size specified by safety regulations and historical knowledge. Whenever the workers move close to the leading edge, the safety envelopes interact. Then data related to these interactions such as time, duration, proximity and number of violations are automatically recorded. This data is used for performance assessment. The training scenarios in the game are updated based on the PSK. Therefore, the accident zones such as unguarded leading-edges and cluttered workplaces can be identified during VR training and rectified before the commencement of actual work.

Figure 3. An example of a training scenario for construction safety involves missing or inadequate guard rails at an elevated work station [26].

4.3 Performance assessment

The data relating to the performance of the players in terms of task execution, completion and safety violations are recorded during training. Automated assessment of the performance of individuals or groups is readily available after completing the training. The decision-makers and instructors can provide feedback to improve the performance. These trained labourers tend to have more situational awareness than those trained in an unrelated work environment without personalised feedback [5, 26]. Examples for data collected from the training scenario in Figure 3: the number of close-call events such as workers moving closer to the leading-edge, and time taken by the workers to detect the hazard, rectify the hazard and complete the task. Each worker can improve their performance in detecting the hazard or rectifying it based on personalised feedback.

4.4 Creating and selecting new training scenarios and updating VR games

After the initial set of training, VR games are updated based on the performance of the labours and feedback from the decision-makers. If most of the players face difficulty performing certain tasks, the training scenarios need to be evaluated. Suppose there is an undetected hazard in the training scenario, and all participants are interacting with it. In that case, it needs to be included, even if it is not part of the upcoming task (for example, a cluttered workplace that may cause slips or trips). If the labours are unfamiliar with the available safety solutions or are underperforming, they should be further trained to achieve the required performance. New safety solutions should be introduced from the library whenever necessary (If guard rails in the leading-edge are being removed frequently, introduce safety nets). The new safety solutions can be generated based on the historical knowledge database. Besides, the newly created safety knowledge from the VR training is added to the knowledge database.

Alternate training scenarios should be introduced, or new training scenarios must be created if the existing scenarios are inadequate (The workers in Figure 3 should wear safety lanyards if the barricading do not provide enough protection). The decision-makers should be informed of any significant safety issues identified in the as-designed model during VR training (for example, issues in the site layout or logistics that may pose frequent and unintended interaction between workers and moving equipment). The VR environments should be updated after rectifying the issues on the construction site.

As the construction work progresses, the VR environment must be updated with the as-built 3D model from the digital twin. The training scenarios are either created or selected from the existing scenarios based on the difference between reality and plan. Therefore, the labours are always trained with the latest VR game before their work. Consider the example of updating in the VR environment with an as-built 3D model that contains unguarded leading edges. Here the program would look through the list of training scenarios and find the scenario linked to the potential incident. The found scenario is then placed on top of the as-built model as intractable objects, such as guardrails. The scenarios will also be created from the information obtained from as-planned process, to ensure workers are trained in upcoming environments. The VR training games are dynamically updated until the completion of the project.

5 Discussion and conclusions

High accident rates in the construction industry are one of the primary reasons for its low productivity. Conventional safety training methods seem to be inadequate for inducing safety awareness in workers. Safety training through VR technologies provides more immersive and interactive training experiences. These training experiences create significant interest in participants and result in enhanced safety performance. The data generated during VR training has great potential for improving the training process yet is seldom explored. Earlier studies have shown that these data can be used for automated performance assessment and provide personalised feedback to the participants.

The current study proposes a new concept for integrating VR training with information streams from the digital twins. The training scenarios are automatically created from the project intent information, project status knowledge, safety regulations and historical knowledge provided by the digital twins. Therefore, the workers can be trained in realistic training environments with tasks relevant to their assigned work. The accidents can be reduced to a great extent due to prior experience in similar work environments. The knowledge generated through dynamic VR training is updated to the digital twin database. Conflicts in site layout, planned processes, or resource allocation can be identified before execution through VR training. Periodic data streams from digital twins enhance training scenarios. Therefore, dynamic VR training is mutually beneficial for digital twins and construction safety management.

6 Challenges and future work

The concepts discussed in the paper aims to explore the possibilities of digital twin and VR for holistic construction safety training. Even though these technologies have been adopted in other industries such as manufacturing, aviation, and health care; the construction industry still lags behind. The current technology readiness level of the construction industry is inadequate for successfully implementing dynamic VR training for safety. Although BIM has been gaining momentum in the industry for the past couple of years, the digital twin technology is relatively new.

The digital twins are expected to deliver the states of the project to update the VR games for training. Most of the time, the quality of data and level of information collected from construction sites are not sufficient to create a realistic training environment. Collecting and frequent streaming of high-quality data through digital twin may be computationally expensive and economically demanding. The high investment in digital twins and dynamic VR training can be justified by reducing accidents and loss of working hours, in addition to improvement in productivity and overall performance of the project. Future work includes validation of the proposed conceptual framework through the information streams from the digital twin.

The nuances of implementing digital twins for a construction project are yet to be explored. For example, it is hard to obtain repeatable and ready-to-use solutions from past construction projects due to the uniqueness and inherent complexity of every project. Therefore, every construction project needs to invest a lot of time and effort in creating project-specific training scenarios and VR environments. Currently, the developer manually creates training scenarios by identifying the semantic relationships of objects and the surrounding environment. Consider a labourer working at height near a leading edge: A human developer would easily understand that barricading the leading edge is not enough to avoid potential accidents. The labourer should be provided with PPE and safety lanyards to avoid potential fall from the height. Therefore, the safety training scenarios should be created with due diligence. This process is often tedious and time consuming for a continuously evolving construction project. The future works explore the possibility of automating the creation of semantically meaningful training scenarios.

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